# Modeling and simulation of fourteen bus system employing D-STATCOM for power quality improvement

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*Abstract:* **This work deals with modeling and simulation of fourteen bus system employing D-STATCOM for power quality improvement. The improvement in voltage stability with D-STATCOM is presented. A 11 level inverter based D-STATCOM is proposed to reduce the harmonics in the output. Voltages at various buses with and without D-STATCOM are presented. The simulation results are compared with the analytical results.**

## I. Introduction

The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices viable and attractive for utility applications. Flexible AC Transmission Systems (FACTS), besides the underlying concept of independent control of active and reactive power flows, are an efficient solution to the reactive power control problem and voltage in transmission and distribution systems, offering an attractive alternative for achieving such objectives. Electric power quality (EPQ) problems mainly include unbalance voltage and current, flicker, harmonics, voltage sag, dip, swell, and power interruption [1]-[5]. These power quality problems may cause abnormal operations of facilities or even trip protection devices. Hence, the maintenance and improvement of electric power quality has become an important scenario today.

The present paper deals with the mathematical modeling of multilevel STATCOM, where, an equivalent value of dc sources (in general, capacitors) over one cycle period is computed using principle of energy equivalence. The mathematical model is developed using this equivalent capacitor value for analysis and control system design purpose. Fourteen bus system is simulated with and without D-STATCOM.

## II. Modeling of statcom

### A. Circuit Model

The voltage source converter based STATCOM is the dominant topology in practice. Figure 1 is the circuit diagram of a typical STATCOM[9].

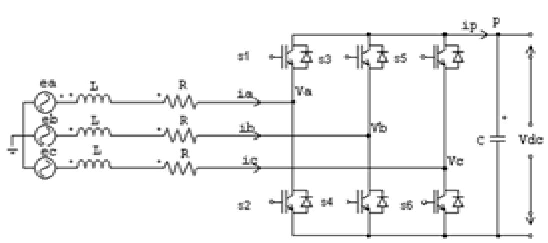


Figure1: Equivalent circuit of STATCOM

Where

| | |
|---|---|
| $i_{a,} i_{b,} i_c$ | line currents |
| $V_{a,} V_{b,} V_c$ | converter phase voltages |
| $e_{a,} e_{b,} e_c$ | AC source phase voltages |
| Vdc=Vpn | DC side voltage |
| $I_p$ | DC side current |
| L | inductance of the line reactor; |
| R | resistance of the line reactor; |
| C | DC side capacitor, |

### B. Mathematical Model

Based on the equivalent circuit of STATCOM shown in Figure 2.1 I can derive the mathematic model of STATCOM as fallow[10[-[12].

From power electronics principles we get

$$i_p = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \tag{1}$$

Where

$D_{kp}$ are switching functions and K= a,b,c

$$i_{ab} = \frac{1}{3}(i_a - i_b),\ i_{bc} = \frac{1}{3}(i_b - i_c),\ i_{ca} = \frac{1}{3}(i_c - i_a)$$

and

$$\begin{bmatrix} V_a - V_b \\ V_b - V_c \\ V_c - V_a \end{bmatrix} = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{pb} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix} Vpn \tag{2}$$

From circuit principles we get

$$Ri_a + L\frac{di_a}{dt} = e_a - V_a \tag{3}$$

$$Ri_b + L\frac{di_b}{dt} = e_b - V_b \tag{4}$$

$$Ri_c + L\frac{di_c}{dt} = e_c - V_c \tag{5}$$

and

$$L\frac{di_{ab}}{dt} = \frac{1}{3}L(\frac{di_a}{dt} - \frac{di_b}{dt}) \tag{6}$$




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this equation can be expanded as below

$$L\frac{di_{ab}}{dt} = \frac{1}{3}[(e_a - V_a) - (e_b - V_b)] - i_{ab}R$$

$$= \frac{1}{3}[(e_a - e_b) - (V_a - V_b)] - i_{ab}R \quad (7)$$

similarly we can get

$$L\frac{di_{bc}}{dt} = \frac{1}{3}[(e_b - e_c) - (V_b - V_c)] - i_{bc}R \quad (8)$$

$$L\frac{di_{ca}}{dt} = \frac{1}{3}[(e_c - e_a) - (V_c - V_a)] - i_{ca}R \quad (9)$$

Writing the above three equations together we have

$$\frac{d}{dt}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3L}\begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} - \frac{1}{3L}\begin{bmatrix} V_a - V_b \\ V_b - V_c \\ V_c - V_a \end{bmatrix} - \frac{R}{L}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (10)$$

By applying equation (2) to equation (10)

$$\frac{d}{dt}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3L}\begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} - \frac{1}{3L}\begin{bmatrix} D_{ap} - D_{bp} \\ D_{pb} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix} Vpn - \frac{R}{L}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (11)$$

and

$$C\frac{dVpn}{dt} = i_p = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (12)$$

It is common practical in power system application to transform 3 phase AC dynamics into orthogonal components in a rotating reference frame. Here components are referred to as the real and reactive components, those that lead to useful work and those that do not respectively. From the power system theory we get the real and reactive currents relative to a rotating reference frame with angular frequency $\omega$ as

$$\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} = P\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (13)$$

and

$$P = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t + \frac{2}{3}\pi) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2}{3}\pi) & -\sin(\omega t + \frac{2}{3}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (14)$$

where

$i_d$ active current component,

$i_q$ reactive current component,

then we have

$$\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} i_a - i_b \\ i_b - i_c \\ i_c - i_a \end{bmatrix} = \frac{1}{3}\left(\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} i_b \\ i_c \\ i_a \end{bmatrix}\right) = \overline{T}^{-1}\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} \quad (15)$$

where

$$\overline{T}^{-1} = \frac{1}{\sqrt{3}}\begin{bmatrix} -\sin(\omega t - \frac{1}{3}\pi) & \cos(\omega t - \frac{1}{3}\pi) & 1 \\ \sin(\omega t) & -\cos(\omega t) & 1 \\ -\sin(\omega t + \frac{1}{3}\pi) & \cos(\omega t + \frac{1}{3}\pi) & 1 \end{bmatrix} \quad (16)$$

if we set Tas the first two 2×3 subspace of matrix T, we can get

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = T\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (17)$$

similarly we can get

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = T\begin{bmatrix} e_{ab} \\ e_{bc} \\ e_{ca} \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} D_d \\ D_q \end{bmatrix} = T\begin{bmatrix} D_{ab} \\ D_{bc} \\ D_{ca} \end{bmatrix} \quad (19)$$

Applying equation (17) to the left part of equation (11)

$$\frac{d}{dt}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3L}\begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} - \frac{1}{3L}\begin{bmatrix} D_{ap} - D_{bp} \\ D_{pb} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix} Vpn - \frac{R}{L}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (20)$$

Applying equations (18) and (19) to equation (11)

$$\frac{dT^{-1}}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + T^{-1}\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \frac{1}{3L}T^{-1}\begin{bmatrix} e_d \\ e_q \end{bmatrix} - \frac{1}{3L}T^{-1}\begin{bmatrix} D_d \\ D_q \end{bmatrix} \cdot V_{pn} - \frac{R}{L}T^{-1}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (21)$$

From power system principles we get

$e_{d} = V_m$

$e_{q} = 0$ and





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$$T\frac{dT^{-1}}{dt}=\begin{bmatrix}0 & -\omega\\ \omega & 0\end{bmatrix} \tag{22}$$

multiply T to both side of equation (21) and applying equation (22), we obtain

$$\begin{bmatrix}\frac{di_d}{dt}\\ \frac{di_q}{dt}\end{bmatrix}=\begin{bmatrix}-\frac{R}{L} & \omega & -\frac{Dd}{3L}\\ -\omega & -\frac{R}{L} & -\frac{Dq}{3L}\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ Vdc\end{bmatrix}+\begin{bmatrix}\frac{1}{3L}\\ 0\\ 0\end{bmatrix}V_m \tag{23}$$

By applying equations (17) and (19) to equation (12) we have

$$\frac{dVdc}{dt}=\frac{1}{C}i_p=\frac{1}{C}\begin{bmatrix}D_{ap}-D_{bp}\\ D_{bp}-D_{cp}\\ D_{cp}-D_{ap}\end{bmatrix}^T\begin{bmatrix}i_{ab}\\ i_{bc}\\ i_{ca}\end{bmatrix}=\begin{bmatrix}D_d\\ D_q\end{bmatrix}^T T^{-T}T^{-1}\begin{bmatrix}i_d\\ i_q\end{bmatrix}=\frac{3}{2C}\begin{bmatrix}D_d\\ D_q\end{bmatrix}^T\begin{bmatrix}i_d\\ i_q\end{bmatrix}.$$

Which leads to

$$\frac{dVdc}{dt}=\frac{dVpn}{dt}=\frac{1}{C}i_p=\frac{3}{2C}\begin{bmatrix}D_d\\ D_q\end{bmatrix}^T\begin{bmatrix}i_d\\ i_q\end{bmatrix} \tag{24}$$

Rearranging equations (23) and (24) we get

$$\frac{di_d}{dt}=\frac{-R}{L}i_d+i_q\omega-\frac{Vdc}{3L}D_d+\frac{1}{3L}V_m \tag{25}$$

$$\frac{di_q}{dt}=-i_d\omega-\frac{R}{L}i_q-\frac{Vdc}{3L}D_q \tag{26}$$

$$\frac{dVdc}{dt}=\frac{3}{2C}i_dD_d+\frac{3}{2C}i_qD_q \tag{27}$$

Finally we find that we can represent the "outer loop" dynamics of STATCOM, the dynamics resulting from any arbitrary switching function , by representing the above equation in its the standard state space form[15]-[18].

$$\frac{d}{dt}\begin{bmatrix}i_d\\ i_q\\ Vdc\end{bmatrix}=\begin{bmatrix}-\frac{R}{L} & \omega & -\frac{D_d}{3L}\\ -\omega & -\frac{R}{L} & -\frac{D_q}{3L}\\ \frac{3}{2C}D_d & \frac{3}{2C}D_q & 0\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ V_{dc}\end{bmatrix}+\begin{bmatrix}\frac{1}{3L}\\ 0\\ 0\end{bmatrix}V_m \tag{28}$$

This completes the nonswitching dynamic model of STATCOM as equation (28). From the model we can see the states of the STATCOM dynamic loop are $i_d$,$i_q$ and $V_{dc}$. $V_{m}$- can be considered as a system constant parameter. The control variables are $D_d$,$D_q$.. ---Note that this is a bilinear system and in our application, full state feedback control of STATCOM, represents a nonlinear system.

## III. Principle of Oeration

The STATCOM consists of a voltage source converter connected in shunt with the system. For the distribution level STATCOM pulse width modulation is typically used to reduce the harmonic output of the converter. Depending on the application, the D-STATCOM may be operated to achieve the following objectives:

1. voltage regulation at a particular ac bus
2. rapid power factor correction of a particular load
3. power factor correction and load balancing and/or harmonic compensation of a particular load.

Basically, the STATCOM system is comprised of three main parts: a VSC, a set of coupling reactors or a step-up transformer, and a controller. In a very-high-voltage system, the leakage inductances of the step-up power transformers can function as coupling reactors. The main purpose of the coupling inductors is to filter out the current harmonic components that are generated mainly by the pulsating output voltage of the power converters [10-12]. The STATCOM is connected to the power networks at a PCC, where the voltage-quality problem is a concern. All required voltages and currents are measured and are fed into the controller to be compared with the commands. The controller then performs feedback control and outputs a set of switching signals to drive the main semiconductor switches of the power converter accordingly. The single line diagram of the STATCOM system is illustrated in Figure 2. In general, the VSC is represented by an ideal voltage source associated with internal loss connected to the AC power via coupling reactors.

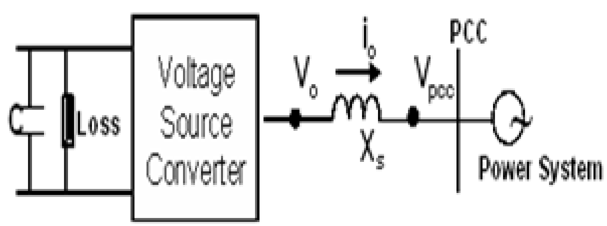


Figure 2(a): Single line diagram of D- STATCOM

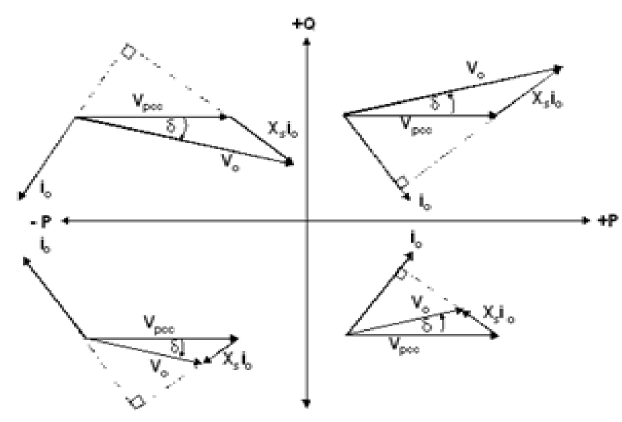


Figure 2(b): Phasor diagram for power exchanges




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The above literature [1] to [12] does not deal with modeling and simulation of 14 bus system using simulink. This work presents modeling and simulation of fourteen bus system employing a D-STATCOM.

## IV. Simulation Results

The Fourteen bus system is considered for simulation studies. The circuit model of 14 bus system without D-STATCOM is shown in Fig 3a. Each line is represented by series impedance model. The shunt capacitance of the line is neglected. The Load voltage and real & reactive power at busses 2 and11 are shown in Figs.3b, 3c,3d and 3e respectively.

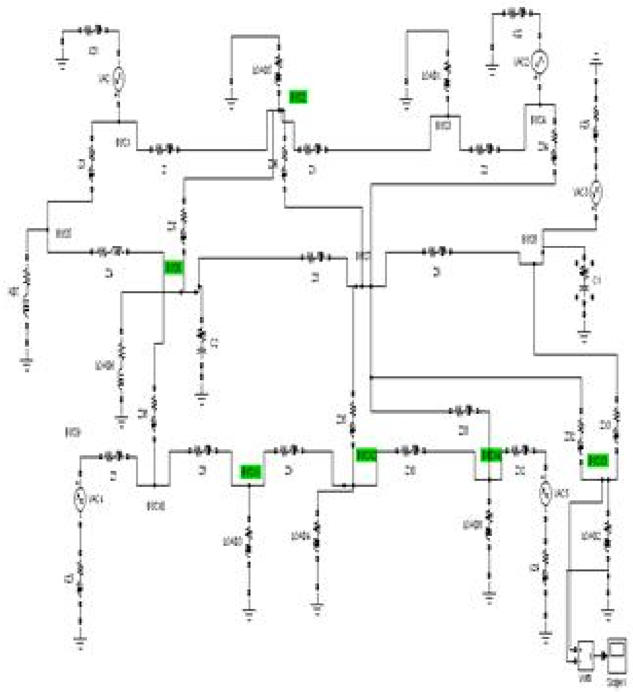

Figure 3.a: Circuit without D-STATCOM model

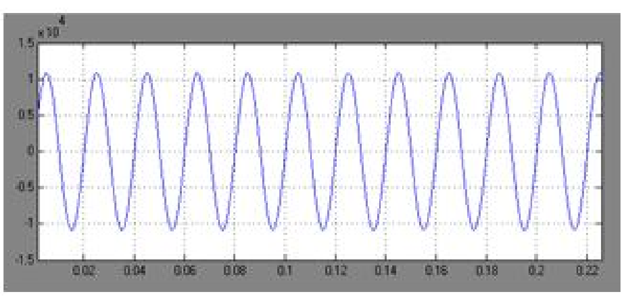

Figure 3.b: load voltage in bus 2

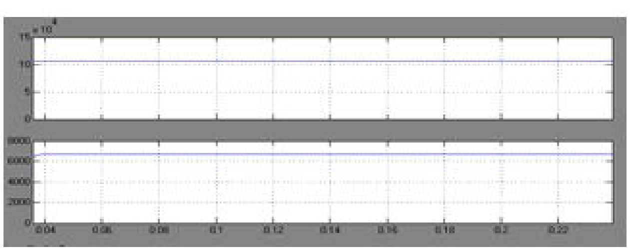

Figure 3c.: Real and Reactive power in bus 2

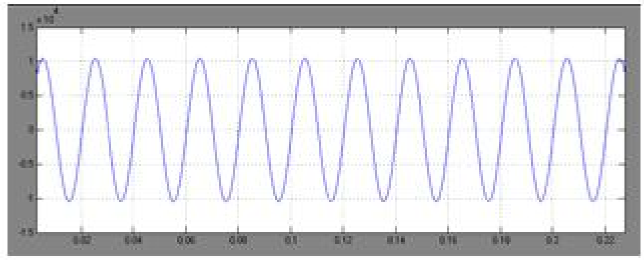

Figure 3.d: load voltage in bus 11

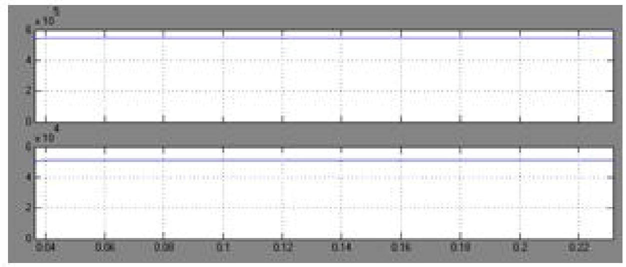

Figure 3.e: Real and Reactive power in bus 11

The 14 bus system with D-STATCOM is shown in Fig. 4a. The D-STATCOM is added to the bus 12 to improve power quality. The reactive power of the loads connected to the nearby buses is studied. The Load voltage, real & reactive powers in the buses 2, and 11 are shown in Figs. 4b, 4c, 4d and 4e respectively. The summary of the reactive power in various buses is given in Table 2. It can be seen that the reactive power increases in the buses near the D-STATCOM. The increase in reactive power is due to increase in the voltage of the nearby buses.

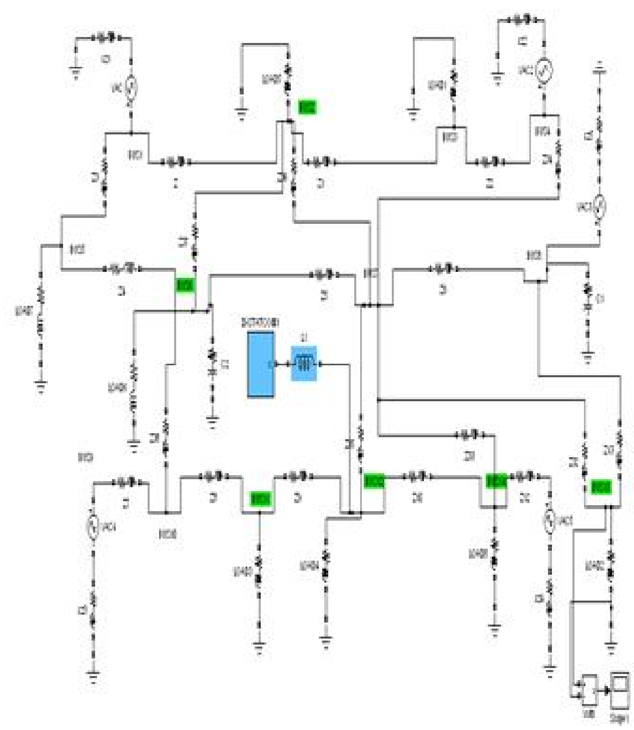

Figure 4.a: Circuit model with STATCOM





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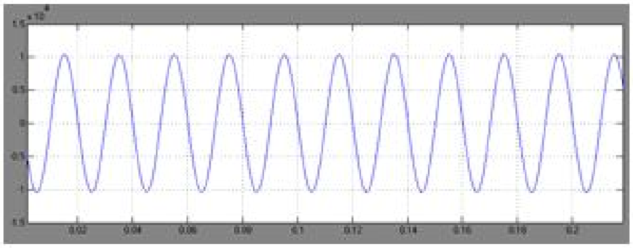

Figure 4.b: Load voltage in bus 2

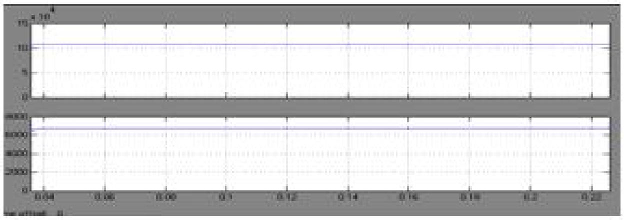

Figure 4.c: Real and Reactive power in bus 2

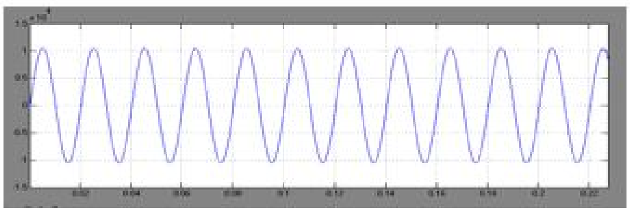

Figure 4.d: Load voltage in bus 11

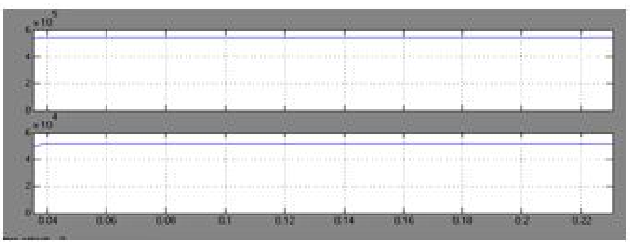

Figure 4.e: Real and Reactive power in bus 11

TABLE I: THE SUMMARY OF THE REACTIVE POWER IN VARIOUS BUSES

| Bus no | Q (MVAR) without STATCOM | Q (MVAR) with STATCOM | VOLTAGE (KV) without STATCOM | VOLTAGE (KV) with STATCOM |
|---|---|---|---|---|
| 2 | 0.066 | 0.0676 | 7314 | 7349 |
| 6 | 1.27 | 1.29 | 6652 | 6672 |
| 11 | 0.0513 | 0.052 | 7411 | 7441 |
| 12 | 0.01 | 0.011 | 7417 | 7454 |
| 13 | 0.029 | 0.030 | 7658 | 7805 |
| 14 | 0.058 | 0.059 | 7345 | 7392 |

## V. CONCLUSION

Fourteen bus system is modeled and simulated using MATLAB SIMULINK and the results are presented. The simulation results of 14 bus system with and without D-STATCOM are presented. Voltage stability is improved by using D-STATCOM. This system has improved reliability and power quality. The simulation results are in line with the predictions. The scope of present work is the modeling and simulation of 14 bus system. This concept can be extended to 64 bus system.




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